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DISTRIBUTION AND PALEOBIOLOGICAL SIGNIFICANCE OF DINOSAUR TRACKS FROM THE JINDONG FORMATION (ALBIAN) IN KOSONG COUNTY, KOREA

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ABSTRACT - The dinosaur ichnocoenosis of the Jindong Formation (Albian), Kosong County represents the world's largest sample (410 mapped trackways) from a single formation. Abundant dinosaur tracks occur in extensive coastal exposures in Hai, Donghae, and Hoewha districts. Ornithopod trackways (249 in number) are the most abundant (61%) in Kosong County. These show a strong tendency (maximum of 18 trackways) toward parallel orientation, which may be an indicator of gregarious behavior. Most footprints range from 25 cm to 45 cm in length, representing sub-adults or adults. A total of 139 trackways (34%) are of sauropod origin. These include the smallest sauropod footprint (pes length 9 cm) currently known in the world and one of the largest trackmakers (pes length 115 cm). The sauropod tracks were made mostly by small, juvenile or sub-adult size classes. Although sauropod trackways indicate social behavior (herding), sauropods were not as gregarious as ornithopods in terms of herd size and consistency of trackways in parallel orientation. There is also some variation among trackways with respect to manus-pes area ratio, which ranges between 1:1 and 1:5. Differences occur in manus position in various sauropod track types as well. Some ornithopod and sauropod trackways show that the animals reduced their walking speed to change direction and not to interfere with other animals walking nearby. Twenty-two trackways (5%) are attributed to theropods, which indicates an interesting predator/prey ratio in the Kosong area. Parallel trackways are absent for theropods, which means that they were not travelling together in herds.

INTRODUCTION

The dinosaur footprints in Korea were first reported from the Cretaceous Jindong Formation in the Dukmyeongri area of Kosong County in 1982 (Yang, 1982). Since then, detailed studies on dinosaur footprints had been made in the Dukmyeongri area (Lim *et al.*, 1989; Lim, 1991; Lim *et al.*, 1994; Lockley *et al.*, 1993; Yang and Lim, 1991). Along with dinosaur tracks, abundant bird tracks were also found in the same region including a bird ichnotaxon, *Jindongornipes kimi*, and at times, on the same bedding plane as dinosaur footprints (Yang *et al.*, 1990; Lockley *et al.*, 1992). Besides the Dukmyongri area of Hai District, abundant dinosaur footprints had been discovered in Donghae District (Baek and Seo, 1998) so that it became necessary to explore dinosaur footprints

Table 1. Mapped dinosaur trackways in each district of Kosong County

HAI D.C.											
Localities	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*Total*
Ornithopod trackways	52	3	15	14	7	17	8	27	13	14	170
Sauropod trackways	14	9	10	5	3	6		7	6	5	65
Theropod trackways	10	1	1				3				15
HAIL D.C.											
Localities	*1*	*2*									
Ornithopod trackways	9	5									14
Sauropod trackways	2										2
Theropod trackways	2										2
DONGHAE D.C.											
Localities	*1*	*2*	*3*	*4*	*5*	*6*					
Ornithopod trackways	14	2	8	9		2					35
Sauropod trackways	11	5	2	4	2	4					28
Theropod trackways	3	1									4
GEORU D.C.											
Localities	*1*										
Ornithopod trackways	4										4
Sauropod trackways	1										1
Theropod trackways											
MAAM D.C.											
Localities	*1*										
Ornithopod trackways	3										3
Sauropod trackways	1										1
Theropod trackways											
HOEWHA D.C.											
Localities	*1*	*3*	*6*	*7*	*10*	*16*	*18*	*19*	*20*		
Ornithopod trackways	2		1		5	2	9	1	1		21
Sauropod trackways	7	1	1	1		1		1	27		39
Theropod trackways			1								1
GAECHEON D.C.											
Localities	*3*	*4*									
Ornithopod trackways	1	1									2
Sauropod trackways	1	1									2
Theropod trackways											
YOUNGHYUN D.C.											
Localities	*1*										
Ornithopod trackways											
Sauropod trackways	1										1
Theropod trackways											

in Kosong County systematically. A total of 14 districts of Kosong County were explored to find dinosaur tracks in this study, resulting in the discovery of multiple dinosaur track-bearing levels from 8 districts. These districts are mostly distributed in coastal areas where outcrops are well exposed along the coastline. Some dinosaur tracks are also found in road cuts, quarries, and stream beds. Approximately 410 dinosaur trackways and 4000 footprints have been mapped from the Jindong Formation, and it represents the world's largest dinosaur ichno-sample from a single formation (Table 1). The purpose of this paper is to briefly describe the nature and pattern, if any, of distribution of dinosaur tracks in each district including the previously published information on Hai and Donghae districts.

GEOLOGICAL SETTING

The Mesozoic beds in South Korea consist of an entirely non-marine, sedimentary succession associated with volcanic activity that increased through time. The whole Mesozoic section is divided into the Daedong Supergroup (Late Triassic to Middle Jurassic), the Myogog Formation (Late Jurassic or Early Cretaceous), and the Gyeongsang Supergroup (Cretaceous) in ascending order. Although extensive paleontological studies have been conducted (mainly on invertebrates and plants), fossil

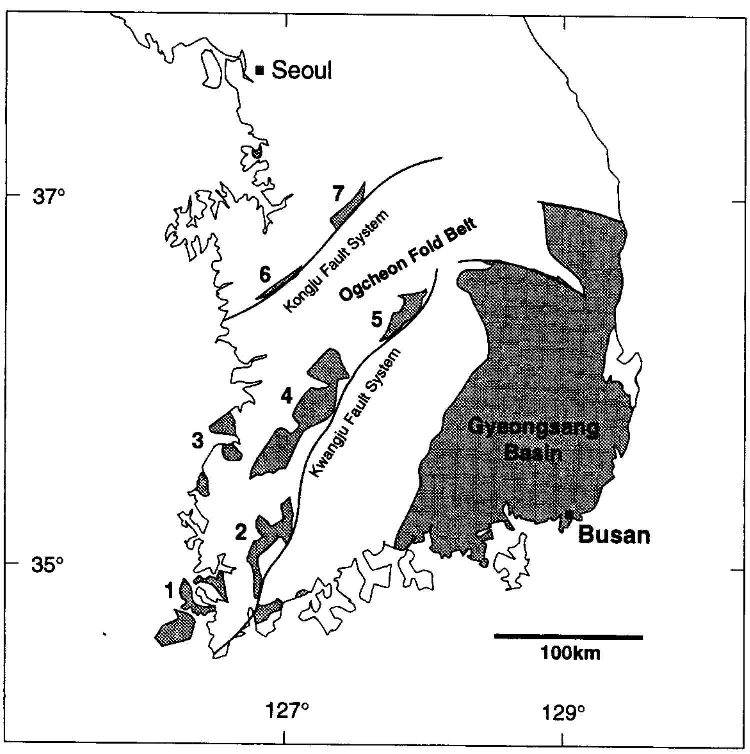

Figure 1. Distribution of Cretaceous basins (shaded) as related to Cretaceous fault patterns in the Korean Peninsula. Numbers indicate smaller Cretaceous non-marine basins subordinate to the Gyeongsang Basin as follows: **1**, Haenam; **2**, Neungju; **3**, Kyokpo; **4**, Jinan; **5**, Youngdong; **6**, Kongju; and **7**, Eumsung.

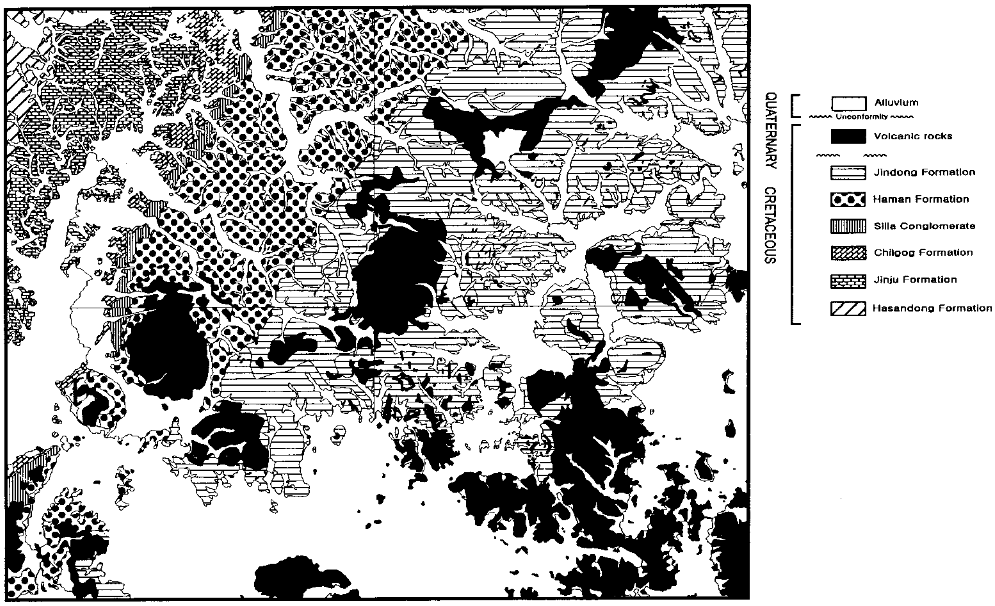

Figure 2. Simplified geologic map of the Sacheon-Samchunpo-Chungmu-Jindong area.

vertebrates are unknown so far from the Myogog Formation and the Daedong Supergroup except for unstudied fishes from the Amisan Formation, South Chungcheong Province (Lee, 1987).

On the other hand, abundant vertebrate faunas have been reported piecemeal from the Cretaceous Gyeongsang Supergroup. The Gyeongsang Supergroup occurs within the Gyeongsang Basin and several small basins (Haenam, Neungju, Jinan, Kyokpo, Yongdong, Kongju, and Eumsung). The Gyeongsang Basin, the largest sedimentary basin in Korea, is widely distributed in the southeastern part of the Korean Peninsula (Fig. 1).

The Haman and Jindong formations are dominantly distributed in Kosong area (Fig. 2). The Jindong Formation is exposed as the coastal cliffs, which is one of reasons that the tracks are discovered frequently in the formation. The Jindong Formation (more than 1000 m thick) consists predominantly of dark gray calcareous mudstones, siltstones, and fine sandstones of lacustrine origin.

Out of 70 samples processed from the Jindong Formation, palynomorph grains are observed in four samples. Among these, only one sample is palynologically productive. A quantitative analysis shows the significant dominance of gymnospermous pollen, such as *Corollina* (40.09%), *Inaperturopollenites* (19.79%), and *Perinopollenites* (19.27%). The presence of *Retimonocolpites* and *Tricolpites* is also noticed. These characteristic angiospermous taxa indicate the Albian age for the Jindong Formation. The composition of the microfloral assemblage indicates the vegetation of a warm and arid climate.

DISTRIBUTION OF TRACKSITES

Hai District

The Dukmyeongri area of Hai District is the best known tracksite internationally (Lockley, 1999) and now protected by the government as the 411th natural monument. Hai District yields the most abundant dinosaur tracks of Kosong County where more than 170 ornithopod, 15 theropod, and 65 sauropod trackways (mapped ones) occur in as many as 203 distinct horizons in a continuously measured section (150 m thick) of the Jindong Formation from 11 localities (Fig. 3). The Dukmyeongri site is well known not only for abundant dinosaur tracks, but also for the type locality of *Jindongornipes kimi* (Lockley *et al.*, 1992). Some of this ichnospecies was found on the same surface as *Koreanaornis hamanensis* at more than 14 horizons in the Dukmyeongri area.

In Hai District as in other districts, ornithopod trackways show a strong tendency toward parallel orientation, which may be an indicator of group behavior. Eighteen parallel ornithopod trackways (average seven parallel trackways) are observable on the 7th horizon of locality 1 (Fig. 4). Most

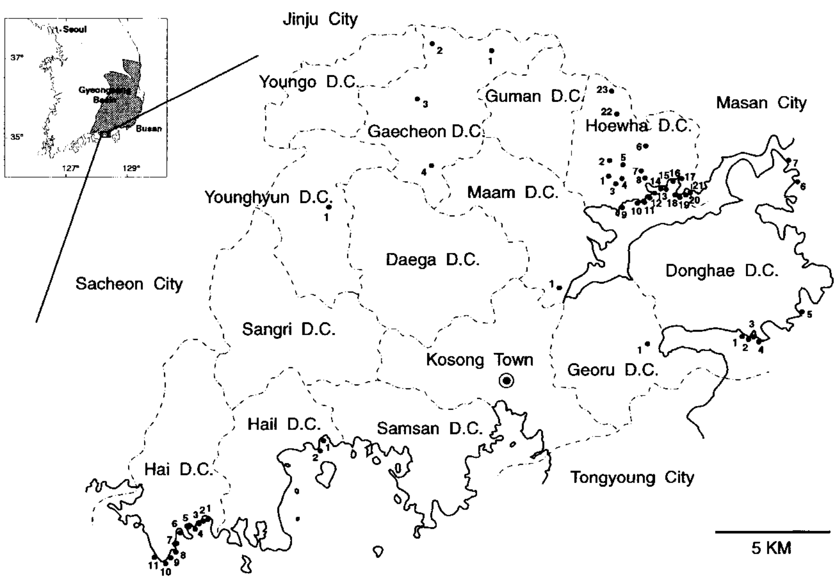

Figure 3. Kosong County map showing localities of dinosaur tracksites by the district mentioned in the text.

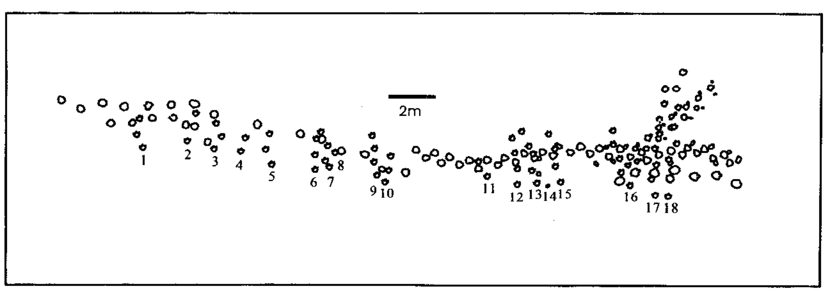

Figure 4. Distribution map of 18 parallel ornithopod trackways from the 7th horizon of locality 1 in Hai District (modified after Lim, 1991)

rnithopod footprints range from 25 cm to 45 cm in length, representing sub-adult or adult animals (Fig. 5A). Although five parallel sauropod trackways are observable on 9th horizon of locality 1, sauropods in Kosong did not seem to travel in large groups overall. This was interpreted as the

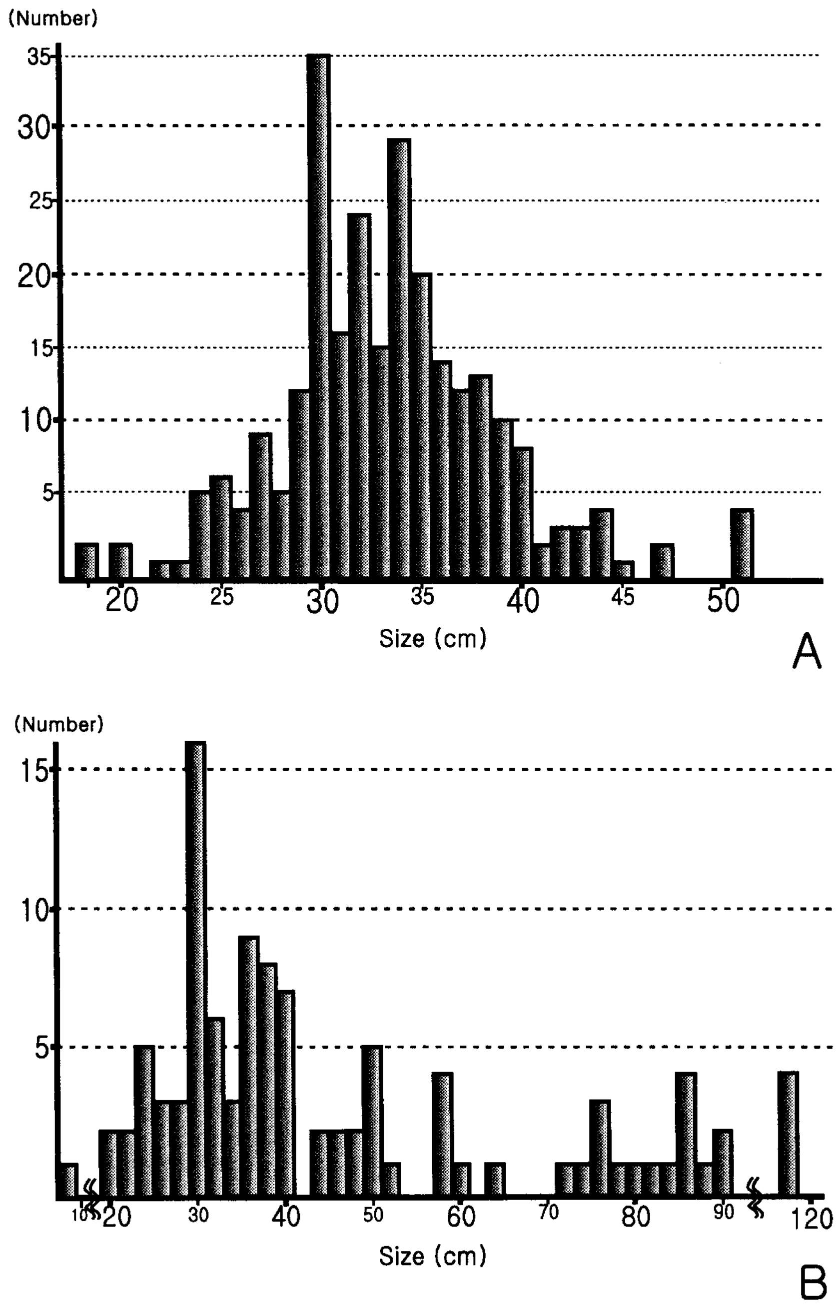

Figure 5. Histograms showing size frequency for ornithopod trackways (**A**) and sauropod trackways (**B**).

trackmakers were too young to engage in herd behavior (Lim *et al.*, 1994) because the sauropod track assemblage in this region is composed mostly of many juveniles, size class 20 to 40 cm of pes footprint (Fig. 5B). Three long sauropod trackways are traceable (32, 31, and 18 consecutive footprints, respectively) from the 7th horizon of locality 3. It is notable that all the sauropod trackways have wide-gauge footprints. From locality 7, well-preserved sauropod tracks are replicated as impressions at the top of igneous sill that intruded the track-rich Jindong Formation (Lockley *et al.*, 1993). Compared with the dominance of ornithopod and sauropod tracks, theropod tracks occupy only a small portion (6%), which implies relatively low predator and prey ratio. The theropod footprint is seldom over 30 cm in length. Randomly oriented four theropod trackways are recorded on the 6th horizon of locality 1.

Locality 8 shows a high density of track-bearing horizons; 37 track-bearing levels from 45 m measured section. Track-rich sequence like this has not been reported previously. From the section, bird tracks (*Jindongornipes kimi*) occur in 7 different horizons including the uppermost horizon (37th), in which they occur on the same surface as ornithopod and sauropod tracks (Lim *et al.*, 1989). Dinoturbations are also common in this region.

Hail District

Six dinosaur track-bearing horizons occur in two localities in which 14 ornithopod, 2 sauropod, and 2 theropod trackways are mapped. In locality 1, one sauropod trackway is parallel to nine ornithopod trackways, which all show parallel orientation, indicating that ornithopod and sauropod dinosaurs were moving together (probably as one group) in a preferred direction.

Donghae District

Donghae District is the second largest dinosaur tracksite in Kosong County. At least 1300 dinosaur footprints were reported previously from 163 track levels in 6 localities (Baek and Seo, 1998). A total of 67 trackways were observed in this study, comprising 35 ornithopod, 28 sauropod, and 4 theropod ones. 15 bird footprints (*Jindongornipes kimi*) were also found in this region (locality 7).

From locality 3, one sauropod trackway containing 11 footprints was found on the mud crack surface. Although details of claw marks are not evident, entire outlines can be seen clearly in most tracks. Average length of manus is 84 cm and pes is 115 cm, which is the largest quadrupedal tracks in Korea (Fig. 6). In particular, the manus prints are circular in shape, showing a unique star shaped internal structure as seen in Uhangri manus-only trackways (Lee and Huh, submitted) although not as prominent as the latter.

Georu District

Three dinosaur track-bearing horizons were found with bird footprints in one locality. Among bird tracks, four webbed-foot bird footprints were recognized which are similar to *Uhangrichnus chuni* described from the Uhangri Formation of Haenam, South Chulla Province (Yang *et al.*, 1995).

Maam District

A new dinosaur track site was found at the construction site of the Kosong intersection of Daejeon-Tongyoung Express Highway in 1999. The ichno-assemblage includes a sauropod trackway and two parallel ornithopod trackways (Fig. 7). The sauropod trackway consists of 38 consecutive manus-pes set extending over a distance of 20 m (Fig. 7B). The manus prints are similar to pes prints in size (both average length is 36 cm, width 32 cm). It is interpreted as the sauropod reduced the walking speed before changing direction based on the pace, which ranges between 72 cm and 88 cm.

The horizon containing two parallel ornithopod trackways occurs 80 cm above the sauropod trackway horizon (Fig. 7A). The left trackway consists of 29 consecutive footprints (average length 37 cm, width 30 cm) extending over a distance of 22 m. The right trackway extends about a distance of 20 m, comprising 16 consecutive footprints (average length 40 cm, width 32 cm). The pace ranges between 54 cm and 90 cm in the left trackway. Whereas, the pace in the right trackway ranges between 100 cm and 120 cm, which indicates that the right ornithopod was moving faster than the left one. Possible interpretation might be the left trackmaker reduced the walking speed (based on strides) not to interfere with the movement of another ornithopod (Fig. 7A, footprints filled in black) and resumed the normal speed after its passing by.

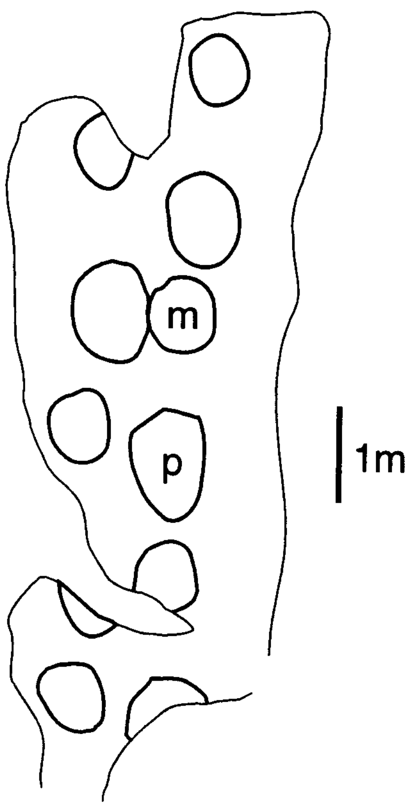

Figure 6. Line drawings of a large sauropod trackway from locality 3 in Donghae District.

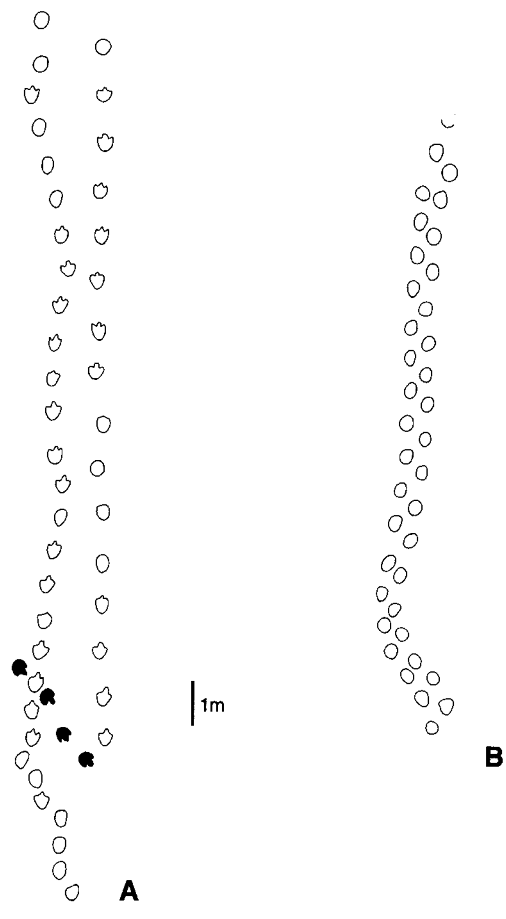

Figure 7. Diagram of two parallel ornithopod trackways (**A**) and one sauropod trackway (**B**) in the Jindong Formation at Kosong intersection locality of Maam District.

Hoewha District

In Hoewha District new large trackway and track-level samples were found. The mapped trackways consist of 27 ornithopods and 10 sauropods from 23 localities. The locality 19 includes the smallest sauropod trackway currently known in the world (Fig. 8A). The trackway consists of 30 consecutive footprints (13 manus and 17 pes impressions). The pes and manus print is 9 cm and 3 cm in length, respectively (i.e., pronounced heteropody). Pes footprint is longer than wide with long axis rotated slightly outward. No pes claw impressions are observed. Manus impressions are ellipsoidal in shape and their long axes are directed anteromedially. A detailed description of this trackway is in preparation.

A long quadrupedal trackway is observed in the locality 20 (Fig. 8B). The trackway consists of 52 consecutive footprints (26 manus and 26 pes impressions), showing a medium-gauge trackway. Pes footprints are longer (30 cm) than wide (23 cm) with long axes rotated to the right. Interestingly, differences occur in the position of manus prints of a single trackway, that is, left manus prints are all located next to the left pes impression, but right manus prints are anterior to the right pes.

Large trackway samples are available from the locality 7, which were found in the Danghangri area in 1999. About 80 footprints belonging to sauropods and ornithopods occur on two shale horizons in the Jindong Formation. The tracks are poorly preserved on the dark gray shale, but a few of trackways are traceable. A large sauropod trackway consisting of eight consecutive pes prints is

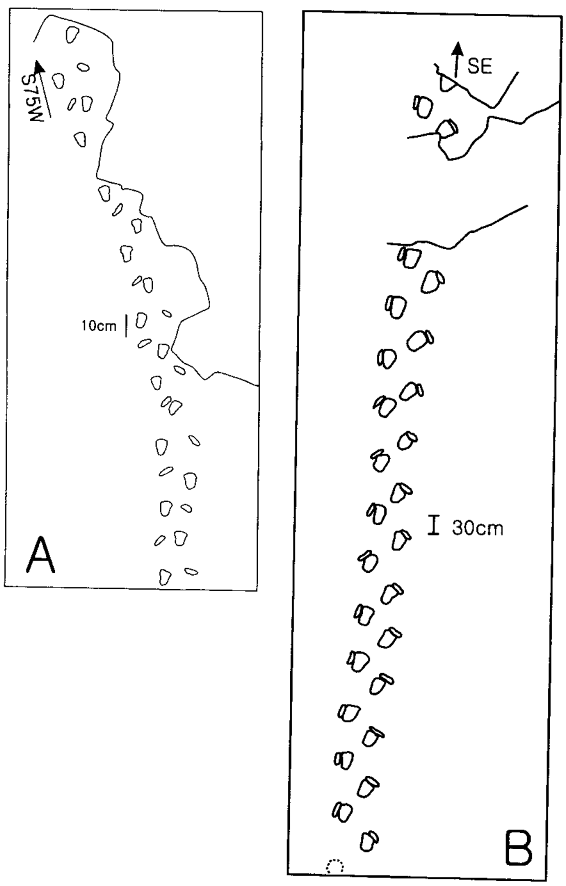

Figure 8. Map showing the smallest sauropod trackway currently known in the world from locality 19 (**A**) and a small sauropod trackway with intriguing manus position from locality 20 (**B**) in Hoewha District.

observed in the upper horizon. They are shallow, rounded, featureless impressions, and probably underprints. These prints are 106 cm in length without clear signs of manus prints. In this trackway, the pes prints completely overprint and obliterate their associated manus prints. The site needs to be studied in detail.

Gaecheon District

Gaecheon District is located in the inland area, and exposures are very limited. Although four dinosaur track localities were discovered in streambeds, most tracks are too poorly preserved to describe in detail.

Younghyun District

A sauropod trackway was discovered in the Haman Formation at the Gaeseong Temple area of Keumtae Mountain. The trackway consists of four manus prints (50 cm in length) and three pes prints (80 cm length), but severely damaged by weathering.

DISCUSSION

Ornithopod, sauropod, and bird trackways in the Kosong region were already reported as the largest sample size currently known in the world (Lim *et al.*, 1994). Along with the previously accumulated documentation from Hai and Donghae districts, a systematic exploration of this study has increased the number of trackways and tracksites in the Jindong Formation significantly. This clearly indicates that Kosong County represents one of the most prolific tracksites in the world for dinosaurs and birds.

The rose diagrams show the differences between ornithopod and sauropod trackway orientation. Whereas the dominant orientation of ornithopod tracks is southwest, that of sauropod tracks is south and southeast (Fig. 9). The differences were also recognized in their different stratigraphic levels and size frequency (Lockley *et al.*, 1991). This phenomenon was explained as the ecologically mutual exclusion to sauropod and ornithopod dinosaurs due to their different population structure, herding, and frequency and timing of occurrence in the area (Lim *et al.*, 1994). However, finding of trackways in Hail District in this study shows that they were travelling together, indicating the evidence of a non-intraspecific herd.

The large dinosaur track samples available in the Jindong Formation provide important paleobiological data related to their walking patterns. For example, differences occur in the manus position in various sauropod tracks and even a single trackway (Fig. 8). It is not yet clear what these differences

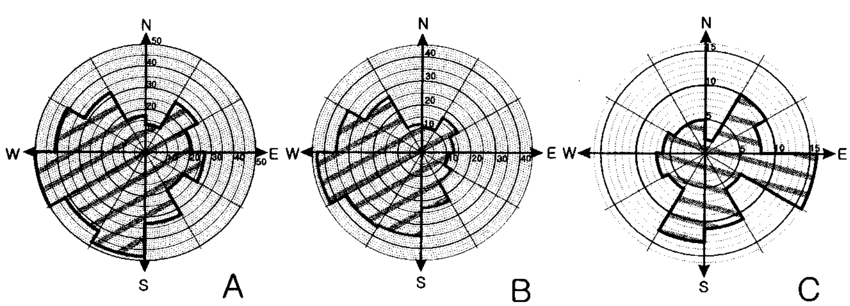

Figure 9. Rose diagrams indicating orientations of **A**, all footprints; **B**, ornithopod footprints; **C**, sauropod footprints of Kosong County.

represented, but it is probably that it can be a reflection of biologic or ecologic factors such as differential taxon, age, and substrate condition. If we could provide detailed ichnotaxonomic assignments to various sauropod track assemblages, it will be an interesting work to see if ontogenetic variations appear in trackways as unique trackway patterns. Although we did not yet explore these intriguing questions systematically, Kosong ichnocoenosis is obviously an opportunity for us to get insights into dinosaur behavior in terms of quantitative and paleoecologic perspectives.

Many sauropod trackways in Kosong County can be also distinguished based on heteropody (manus-pes area ratio), which ranges between 1:1 and 1:5. Some sauropod dinosaurs had strong heteropody inherent from the primitive condition, bipedality (Gauthier, 1986) as revealed by footprints (Farlow *et al.*, 1989). The manus-pes area ratios varies by place and time; range between 1:2 for sauropod trackways from the Middle Jurassic of Portugal (Santos *et al.*, 1994), 1:3 for *Brontopodus birdi* from the Cretaceous of Texas (Farlow *et al.*, 1989), and 1:4 to 1:5 for *Parabrontopodus mcintoshi* from the Late Jurassic of Colorado (Lockley and Rice, 1990; Lockley *et al.*, 1994). However, some of Kosong sauropods appear to have had unusually large manus similar to pes in size. In sauropod trackways found in Maam and Donghae districts, the manus-pes area ratios are 1:1 (Fig. 7B) and 1:1.2 (Fig. 6), respectively. The differences in heteropody of sauropod trackways are known to have the taxonomic significance (Lockley *et al.*, 1994), so that they are indicative of the existence of unknown species of sauropod, not available yet from the body fossil record. Therefore, it can be inferred that diverse sauropods lived during the Jindong time based on the ichnological data such as the manus position, heteropody, and track morphology.

With detailed analysis of tracks, it is also necessary to elucidate the causes of unusually high frequencies of multiple track-bearing levels in this area. Most tracks occur in dark gray shales and siltstones, but some are associated with a fine-grained, wave ripple-marked sandstones with desiccation structures, indicating a shallow subaqueous environment. The abrupt changes from subaerial to subaqueous sedimentary facies are indicative of small-scale water-level fluctuations in this area. High organic matter content and common framboidal pyrite in the dark gray shale suggest that deposition occurred in a reducing environment with relatively high pH and silica concentration. This probably accounts for the low diversity of body and invertebrate trace fossils at the site other than dinosaur and bird tracks. In general, the formation is characterized by cyclic fining-upward sequences, which is believed to have been controlled by subsidence of the basin caused by tectonic movements associated with volcanic activity. However, this inference should be supported by further detailed sedimentological and stratigraphic analysis, which could provide conclusive evidence for sedimentary cycles of the Jindong Formation.

The Jindong trackway samples from Kosong County provide a remarkable ichnological resource for further study of many aspect of dinosaur paleobiology. It is therefore necessary to make continuous exploration of the Jindong Formation systematically to understand the geological and biological history of Korea using vertebrate fossils.

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